Augmenting the DGPS Broadcast with Emergency Information

Richard J. Hartnett, Peter F. Swaszek, and Keith C. Gross

Abstract

Differential GPS, or DGPS, is a medium frequency radio system that is used worldwide for the broadcast of differential corrections to users to improve the accuracy and integrity of the GPS. This communications system works by digitally modulating radio signals broadcast from a network of marine radio beacons operating in the 283.5-325 kHz radio band. The modulation scheme called Minimum Shift Keying (MSK) is used to transmit the correction data at typical data rates of between 50 and 200 bits per second. The U.S. Coast Guard has pioneered the use of MSK for transmission of differential GPS corrections, and has provided over ten years of worthy service with the system. In this paper we suggest that the DGPS system has significant capability for use beyond that of its current mandate; specifically, there exists the potential for concurrently transmitting a second information-bearing signal on the beacon signal. We believe that this simultaneous transmission of the current navigation correction information (the primary channel) and additional messaging (perhaps DHS emergency messaging or other relevant information) could be accomplished at very minimal cost, and with minimal impact on current users, using a technique we have called phase trellis overlay.

Introduction

During times of national or regional emergencies, dependable interagency communications linking all levels of government and response agencies, as well as the general public, is absolutely critical. Major national and regional events such as 9/11 and Hurricane Katrina certainly highlight the need. Critical information such as a change in the national threat level by the Department of Homeland Security must arrive to the intended audience reliably and on time. During critical incidents, radio and television coverage may become disrupted, cellular communication systems may be quickly overwhelmed, and police and emergency communications may become intermittent.

It has been suggested that SMS messaging can be used as a reliable means of communication, and is a logical choice for disseminating critical information to user groups during times of disaster.[1] Such views have prompted many municipalities, colleges/universities, and corporations, to purchase services from SMS-based emergency messaging providers. Unfortunately, due to the fundamental architecture of cellular networks, simulation and analysis by Traynor suggest that these systems will likely fail to deliver high volumes of emergency messages over short periods of time, such as we might experience during times of disaster.[2] Additional limitations of SMS include: (1) cellular networks are not designed to deliver emergency-scale traffic loads, and expend significant overhead just to locate a target mobile device to negotiate a transfer; (2) source authentication is impossible, making fraudulent alerts easy to send; (3) geographic targeting (i.e. sending messages to users in a certain geographic area) is very challenging; and (4) SMS cannot be considered a “real-time service” as significant messaging delays can occur, and delivery order is not necessarily “first in, first out.”[3]

Proposed System Overview

To mitigate some of these limitations, and to provide better building penetration from the use of a lower frequency carrier signal, we propose that the current Differential GPS (DGPS) system could be used very effectively as a Homeland Security Messaging system. Our vision is that all emergency messaging could be routed through a Department of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAR 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **Augmenting The DGPS Broadcast With Emergency Information**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Coast Guard Academy,New London,CT,06320**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
HOMELAND SECURITY AFFAIRS, SUPPLEMENT 3 (MARCH 2011),Government or Federal Purpose Rights License

14. ABSTRACT
Differential GPS, or DGPS, is a medium frequency radio system that is used worldwide for the broadcast of differential corrections to users to improve the accuracy and integrity of the GPS. This communications system works by digitally modulating radio signals broadcast from a network of marine radio beacons operating in the 283.5-325 kHz radio band. The modulation scheme called Minimum Shift Keying (MSK) is used to transmit the correction data at typical data rates of between 50 and 200 bits per second. The U.S. Coast Guard has pioneered the use of MSK for transmission of differential GPS corrections, and has provided over ten years of worthy service with the system. In this paper we suggest that the DGPS system has significant capability for use beyond that of its current mandate; specifically, there exists the potential for concurrently transmitting a second information-bearing signal on the beacon signal. We believe that this simultaneous transmission of the current navigation correction info mation (the primary channel) and additional messaging (perhaps DHS emergency messaging or other relevant information) could be accomplished at very minimal cost, and with minimal impact on current users, using a technique we have called phase trellis overlay.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Homeland Security (DHS) messaging server, which suggests that upon system installation, outside users would be required to establish trusted relationships (via issued certificates) with that DHS emergency messaging server. Validated messages from authenticated users could then be transferred from DHS to the U.S. Coast Guard Navigation Center, Alexandria, VA, and then sent to individual DGPS stations for immediate transmission.

Such a nationwide communications system could, for example, disseminate information when the national threat level was raised or lowered, report a specific threat in a given area (i.e. severe weather, flood, fire, airplane crash, etc.), assist with natural disaster coordination, or provide suspect description and alert. The DGPS system could provide a highly reliable communications system, with the ability to broadcast a short (SMS length) message across the entire country in less than thirty seconds from time of message initiation. Such a system could also cover the offshore areas within our territorial waters, and territories outside the continental United States such as Alaska, Hawaii, Puerto Rico, etc. Coordinated from a central location (USCG NAVCEN), the proposed system would operate for up to forty-eight hours after the loss of commercial electrical power (as does the current NDGPS system), when other communication systems may be down.

A number of key advantages of using the DGPS system include: (1) near-nationwide coverage with high availability (see Figure 1); (2) fast message propagation throughout the service area; (3) centralized Coast Guard command and control at USCG NAVCEN, Alexandria, VA; (4) high resistance to spoofing; and (5) DGPS signal penetration into buildings and remote geographic areas.

This paper discusses the potential use of the U.S. Coast Guard's (USCG) Differential Global Positioning System as a nationwide emergency communications system, which could serve all levels of government, emergency response organizations, and the general public. Since there is minimal "excess capacity" to transmit additional information using the current MSK messaging scheme (i.e. we are not proposing use of one of the undefined or reserved message types in the RTCM DGPS signal specification for emergency messaging), we propose altering the MSK signal itself so that (1) we create an alternate channel for message dissemination (available all of the time) and (2) we do not significantly impact the legacy users of the DGPS system.

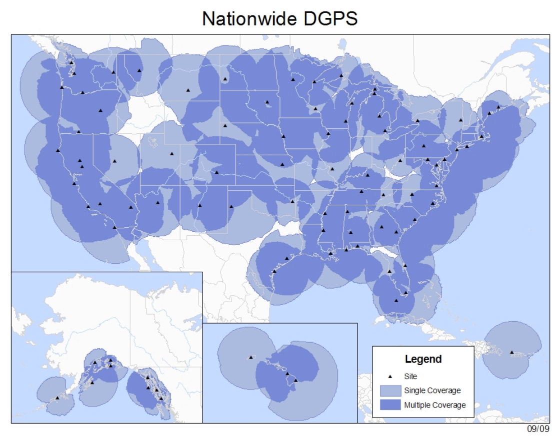

Figure 1. DGPS coverage as of September 2009 (USCG NAVCEN, 2010).

PREVIOUS WORK AND BACKGROUND

The DGPS system is a medium-frequency (between 283.5kHz and 325kHz) radio system that is used worldwide for the broadcast of differential corrections to GPS users. Carrier modulation is MSK, which is a continuous phase frequency shift keying (CPFSK) modulation technique that is *spectrally compact*, meaning that it occupies minimal bandwidth relative to the bit rate. The U.S. Coast Guard has pioneered the use of MSK modulation for sending GPS correction information.

A new generation of DGPS/radio beacon was envisioned by Hartnett et al. in which each radio beacon would be a hybrid datalink capable of accommodating both legacy DGPS signals (50/100/200 bps) and new data channels (500-1000 bps for RTK style observables, detailed NOAA troposphere and ionosphere models, precise orbit data, and homeland security messaging).[4] For these applications, it was envisioned that the system would need to be able to send 500 bps or so without disrupting the legacy signal or legacy receiver performance. That paper

compared two approaches, one of which being the CPFSK phase trellis approach discussed here.

Extending this concept, Swaszek et al. highlighted development of a test bed modulator to assess the impact of the additional modulation on commercially available legacy receivers, and reported preliminary results.[5] Of particular concern was that the new high-rate signal must not significantly impact the performance of legacy DGPS receivers. More specifically, it must not interfere with legacy signal acquisition, tracking, or legacy data demodulation. Also considered were co-channel interference and adjacent channel interference of a secondary communications channel.

Soon afterwards, Johnson et al. described investigations into the impact of the transmitter (amplifier through antenna) on the composite phase trellis overlay signal, recognizing that the composite signal has wider bandwidth than standard MSK.[6] Also discussed in this paper was the development of a prototype receiver for the enhanced signal structure.

Hartnett et al. proposed a promising new class of trellises that lends itself to closed-form expressions for signal distances, and convenient relationships for bandwidth costs,[7] thereby making signal set optimization a relatively straightforward exercise.

Brief Review Of The Phase Trellis Overlay

We begin with a brief review of the phase trellis overlay concept. The legacy DGPS signal is transmitted using minimum shift keying (MSK) whose time domain description can be written

$$s(t,\beta) = \sqrt{\frac{2E_b}{T}}\sin(\omega_0 t + \varphi(t,\beta))$$

in which the phase $\varphi(t,\beta)$ depends upon the data sequence β and follows a continuous trajectory.[8]

A common visual representation for MSK is a diagram showing how the sinusoidal signal's phase progresses over time. With modulation index ½, the MSK waveform gains or loses 90° ($\pi/2$ radians) every bit interval; hence, the resulting phase paths remerge every other bit period and the phase diagram can be drawn as a tree as in Figure 2. (Recognizing that sinusoidal phase is cyclic modulo 360°, this can also be drawn as a trellis.) In this diagram, the horizontal axis is time with horizontal spacing between adjacent circles equal to the bit interval T. The vertical axis is phase with vertically adjacent circles being 180° apart; the full set of phase values at the bit interval endpoints range through 90° steps.

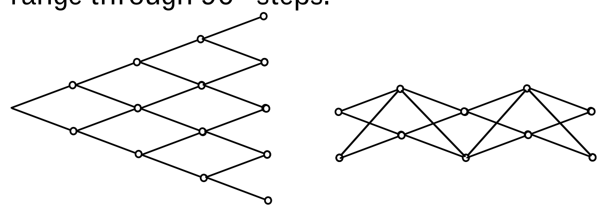

Figure 2. Traditional MSK phase diagram (phase vs. time).

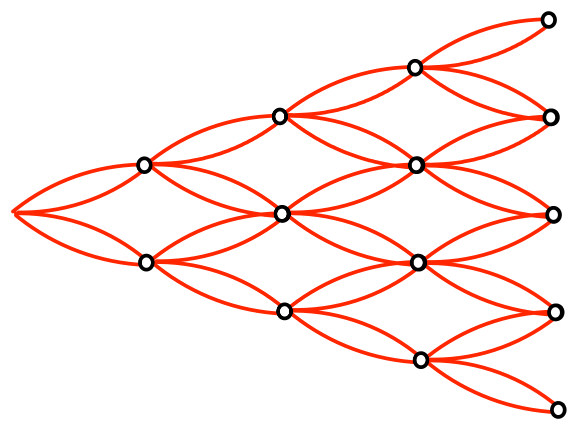

Figure 3. Double rate phase overlay diagram.

The concept of the *phase trellis overlay* approach to increasing the DGPS data rate is to add additional phase paths to the diagram. Specifically, we constrain the phase to go through the same set of phase values at the ends of each bit period, but allow different trajectories between each. For example, Figure 3 shows a phase tree diagram with double the bit rate of MSK; each original path is now split into two. Our view is that the set

of circles traversed with this augmented trellis will be the same as those determined by the legacy DPGS transmission; the actual paths to go from circle to circle will vary depending upon the additional data bits.

Clearly additional paths could be added to further increase the data rate (such as shown in Figure 4 which shows how one pair of paths – legacy 0 and 1 – could be expanded into 3 bits, 8 potential paths). In previous work we restricted our choices of phase trellis overlays (which represent deviations from a legacy MSK linear trellis) to be piecewise linear (as in the example shown in Figure 4).[9]

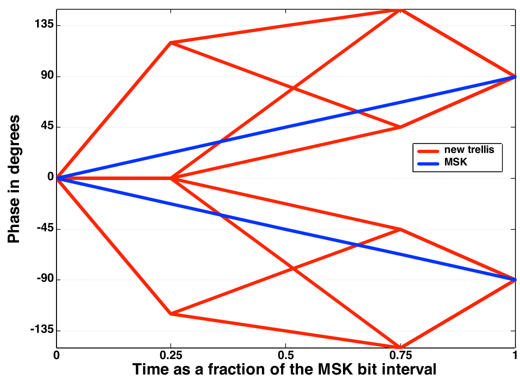

Figure 4. Example of 600 bps phase overlay modulation with piecewise linear trellises (assuming 200 bps legacy and 400 bps overlay).

Hartnett et al. presented an alternative functional form of the overlay signal that offers the potential for reducing the resulting bandwidth as well as providing closed-form expressions for signal distances[10] making signal set optimizations more straightforward. The general idea is to find phase trajectories that (1) minimize impact to legacy DGPS systems, and (2) provide good signal distances for reliable overlay demodulation. Those new phase overlays from could be considered as an "FM overlay" to the original phase trellis.

FM Overlay Trellis Concepts

Over one bit period [O, *T*] the original (legacy) MSK signal can be expressed as

$$s_1(t) = \sqrt{\frac{2E_b}{T}} \sin\left(\omega_0 t + \frac{\pi t}{2T}\right)$$

$$s_0(t) = \sqrt{\frac{2E_b}{T}} \sin\left(\omega_0 t - \frac{\pi t}{2T}\right)$$

where the "excess phase" terms above create a ramp in phase changing by 90 degrees over *T* seconds. Generalizing these expressions, we write a generic CPFSK signal as

$$s(t) = \sqrt{\frac{2E_b}{T}} \sin(\omega_0 t + \varphi(t))$$

The envisioned overlay trellis for MSK consists of such a functional form with various phase functions φ(t) .

If we wish to examine the effects of the overlay trellis on a legacy MSK receiver, we can represent the new signals in the MSK *signal space.* For legacy MSK, since $s_1(t)$ and $s_0(t)$ are orthogonal, we get coordinates in the legacy MSK space of

$$s_1(t) \Leftrightarrow \left(\sqrt{E_b}, 0\right)$$

$$s_0(t) \Leftrightarrow \left(0, \sqrt{E_b}\right)$$

Of significance is that the signals are $\sqrt{2E_b}$ apart. This distance, used as the argument to a Gaussian cumulative distribution function, describes the system's bit error performance in typical channel noise. Figure 5 shows this signal space for MSK: the red dots correspond to the two (orthogonal) signals, the blue circle describes all signals of constant energy, and the red line shows the decision boundary for a linear receiver. As noise causes the received signals to move from their nominal locations in signal space, the further potential signals are from the red

boundary, the better the legacy MSK performance.

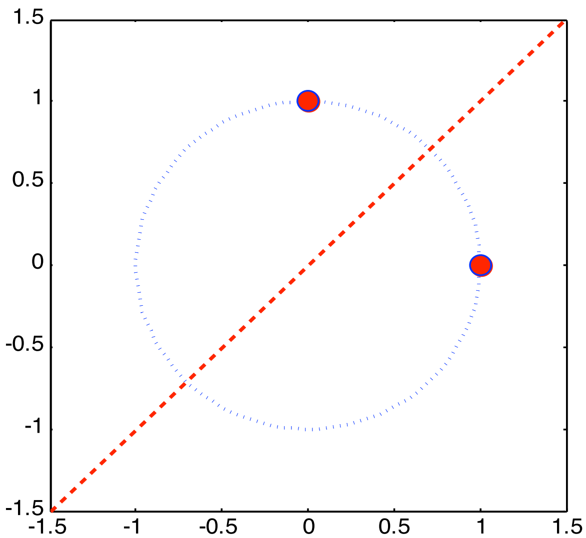

Figure 5. MSK signal space.

For a generic CPFSK signal, the MSK signal space representation is

$$s(t) \Leftrightarrow \left(\rho_1\sqrt{E_b}, \rho_0\sqrt{E_b}\right)$$

with coordinates determined by the correlation coefficients

$$\rho_1 = \frac{1}{\sqrt{E_b}}\int_0^T s(t)\sin\left(\omega_0 t + \frac{\pi t}{T}\right)\,dt$$

and

$$\rho_0 = \frac{1}{\sqrt{E_b}}\int_0^T s(t)\sin\left(\omega_0 t - \frac{\pi t}{T}\right)\,dt$$

(Basically these are projections of the signals onto the orthogonal MSK signals.) Again, for any type of modification of the original MSK signal, we will be interested in the signal space locations of the resulting signals with respect to that red boundary.

Hartnett et al. proposed a more general class of phase trellis overlays for a secondary communications channel,[11] where the new signals are defined over one bit period as

$$s_{1a}(t) = \sin\left(\omega_0 t + \frac{\pi t}{2T} + \alpha\sin\left(\frac{\pi t}{T}\right)\right)$$

$$s_{1b}(t) = \sin\left(\omega_0 t + \frac{\pi t}{2T} - \alpha\sin\left(\frac{\pi t}{T}\right)\right)$$

$$s_{0a}(t) = \sin\left(\omega_0 t - \frac{\pi t}{2T} + \alpha\sin\left(\frac{\pi t}{T}\right)\right)$$

$$s_{0b}(t) = \sin\left(\omega_0 t - \frac{\pi t}{2T} - \alpha\sin\left(\frac{\pi t}{T}\right)\right)$$

(Note that we have assumed $\sqrt{\frac{2E_b}{T}} = 1$ with no loss in generality.) By restricting the form of modulation to a sinusoidal variation with a single parameter α, we simplify analysis and optimization. Further, we limit the problem to 2 bits per interval (a doubling of the MSK data rate; earlier work allowed larger increases).

Figure 6 simultaneously shows 4-tuples of signals (one signal of each color) for four different values of α; the dotted red and black lines are the legacy MSK signals. Figure 7 shows the resulting spectrum, again for a range of values of α. We note that small α, in the range 0.2 to 0.4, results in a modest increase in bandwidth with respect to MSK.

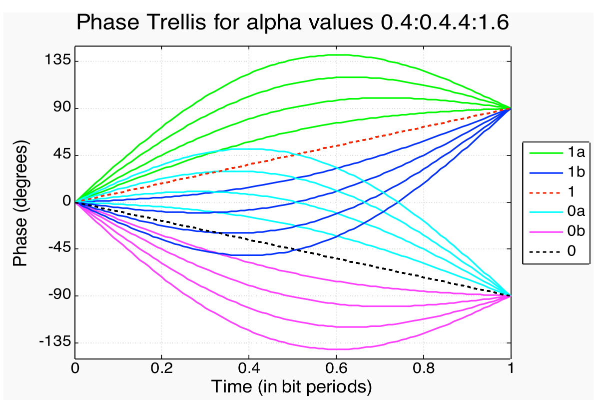

Figure 6. Phase trajectories for varying values of α.

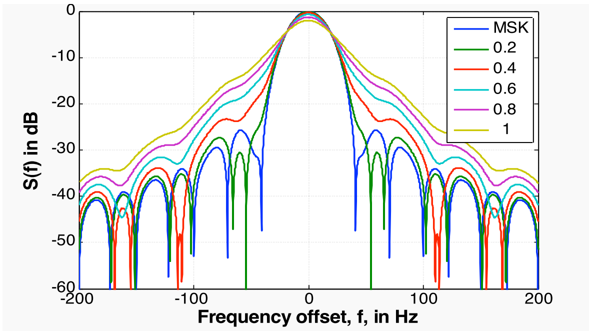

Figure 7. Spectral densities for proposed trellis overlay as *α* is varied.

SIGNAL LOCATIONS IN LEGACY MSK SIGNAL SPACE

Of interest is the location of these new CPFSK signals in MSK signal space, so as to determine any performance degradation of a legacy MSK receiver. Detailed derivations from Hartnett et al. determined that

$$s_{1a}(t) \Leftrightarrow \left(J_0(\alpha)\sqrt{E_b}, J_{-1}(\alpha)\sqrt{E_b}\right)$$

$$s_{1b}(t) \Leftrightarrow \left(J_0(\alpha)\sqrt{E_b}, J_1(\alpha)\sqrt{E_b}\right)$$

$$s_{0a}(t) \Leftrightarrow \left(J_1(\alpha)\sqrt{E_b}, J_0(\alpha)\sqrt{E_b}\right)$$

$$s_{0b}(t) \Leftrightarrow \left(J_{-1}(\alpha)\sqrt{E_b}, J_0(\alpha)\sqrt{E_b}\right)$$

where $J_n(\alpha)$ is the Bessel function of the first kind of the n^{th} order, or

$$J_n(\alpha) = \frac{1}{\pi}\int_0^{\pi} \cos(\alpha \sin\theta - n\theta)\ d\vartheta$$

Observe that these are signal projections into "legacy MSK signal space," and are a function of *α*; specific values of these projections are shown in Figure 8 for several values of α. As expected, they spread apart (away from the nominal MSK signal points) as α increases, eventually crossing the diagonal boundary (which would cause legacy MSK bit errors). From this information we can calculate signal space locations (Figure 8), inter-signal distances, and predict performance degradation from adding our new channel.

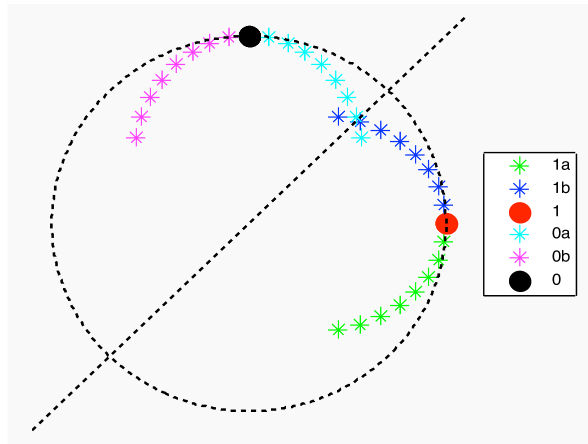

Figure 8. Signal projections into legacy MSK signal space for varying values of *α*.

SIGNAL DISTANCES IN THE HIGHER DIMENSIONAL SIGNAL SPACE

In order to evaluate the communications performance of the added channel, Hartnett et al. calculated the signal distances in the new higher dimensional signal space (higher since there are more signals).[12] The generic definition of distance *d*, when applied to two phase modulated signals and , is

$$d_{j,k} = \sqrt{\int_0^T \left[s_j(t) - s_k(t)\right]^2 dt} = \sqrt{2E_b\left(1 - \frac{1}{T}\int_0^T \cos\Delta\theta(t)\ dt\right)}$$

in which $\Delta\theta(t) = \varphi_j(t) - \varphi_k(t)$ is the phase difference of the two signals. Resulting signal distances from Hartnett et al. are summarized in Table 1.[13]

Table 1. Signal distance calculation summary.

$d_{1a,1b} = d_{0a,0b} = \sqrt{2E_b\left(1 - J_0(2\alpha)\right)}$
$d_{1a,0b} = d_{0a,1b} = \sqrt{2E_b\left(1 - J_{-1}(2\alpha)\right)}$
$d_{1a,0a} = d_{1b,0b} = \sqrt{2E_b}$

PERFORMANCE CONSIDERATIONS

Note that higher values of α allow greater signal distances for the trellis overlay at a cost of increased degradation of the legacy channel. For purposes of illustration, we choose a value of α = 0.4. The minimum signal distance in the higher dimensional signal space (from Table 1) becomes

$$d_{1a,1b} = d_{0a,0b} = \sqrt{2E_b\left(1 - J_0(2\alpha)\right)} = 0.5545\sqrt{E_b}$$

This minimum distance is of interest since it will dominate the baseline performance of the DHS messaging (trellis overlay) channel. Assuming no data retransmission or channel coding, equal data rates on legacy and trellis overlay channels, and equivalent antenna/receiver capabilities for legacy and trellis overlay channels, we can think of this distance as being 8.13dB below the legacy DGPS signal distance ($\sqrt{2E_b}$), so predicted coverage for the DHS messaging system would be equivalent to a legacy DGPS transmission at 8.13 dB lower signal power.

For purposes of illustration, we now consider coverage tradeoffs for a single DGPS station at Sandy Hook, NJ, transmitting at 200 bits/sec. We assume that the required signal level for coverage is 37.5 dB (1µv/m).[14] Figure 9 shows the current approximate DGPS coverage (in yellow) for this station; the red area shows the expected coverage for the trellis overlay messaging system from Sandy Hook. Note that New York metropolitan areas are still included in this depiction. If more coverage is desired or if less sensitive receivers (i.e. smaller antennas) are employed, one can "buy back" much of this 8 dB loss through channel coding, at a cost of reduced information rate. For example, Figure 10 shows the coverage for the legacy signal remaining at 200 bps while the overlay signal is reduced to 100 bps (essentially doubling the power in the overlay signals).

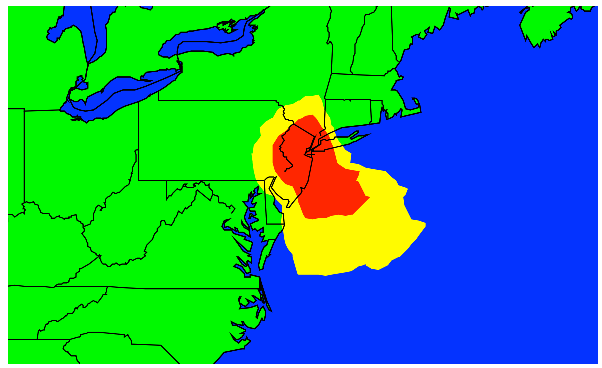

Figure 9. Approximate coverage diagram for DHS messaging users (200 bps trellis overlay) of Sandy Hook DGPS station (red) compared to current coverage (yellow).

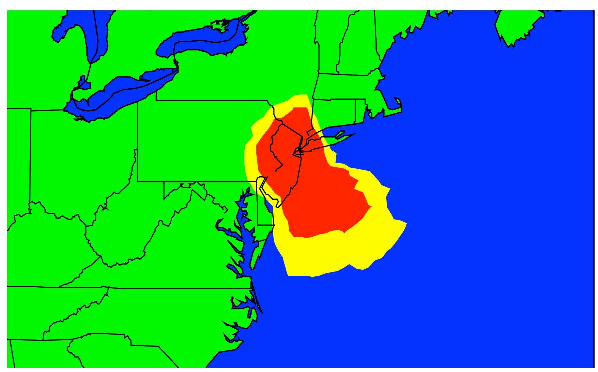

Figure 10. Approximate coverage diagram for DHS messaging users (100 bps trellis overlay) of Sandy Hook DGPS station (red) compared to current coverage (yellow).

With respect to impact to the legacy DGPS user, we refer to Figure 11 which shows in red the coverage for the legacy user in the presence of the new signals. In calculating this coverage we note that signals $s_{0a}(t)$ and $s_{1b}(t)$ are now at a distance of $1.1235\sqrt{E_b}$ (for

α = 0.4) vice $\sqrt{2E_b}$ (for legacy MSK), which represent approximately a 2 dB loss to legacy DGPS performance.

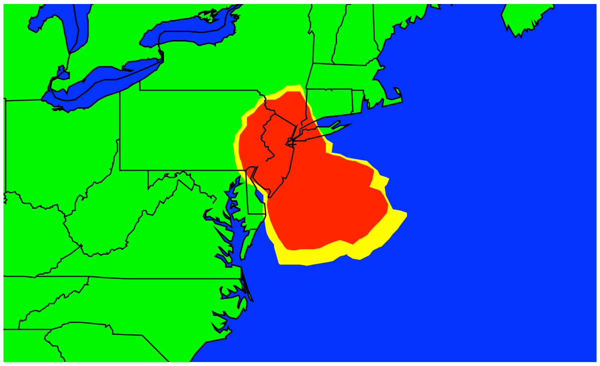

Figure 11. Approximate coverage diagram for legacy users of Sandy Hook DGPS station before (yellow) and after (red) implementation of trellis overlay messaging.

CONCLUSIONS/FUTURE WORK

Here we propose the idea of a low-data-rate, robust, cost-effective communication system augmentation that could be used for a variety of purposes. One possible purpose is the dissemination of emergency messages. Just as "small footprint" GPS receivers are included in cellular telephones, we envision that "small footprint" trellis overlay receivers could be built inside cellular telephones to monitor DHS messages, and then provide appropriate user warnings via audible/text alert. Coverage plots provided highlight that this messaging system has the potential to provide significant coverage, with minimal legacy DGPS coverage degradation.

Our clear next step is to develop a software tool that allows analysis of CONUS coverage as a function of transmitter power and the parameter α with the goal of establishing broad coverage of the new messaging system over major metropolitan areas while having minimal impact on legacy users. Other future work will include the investigations of:

- calculation of equivalent signal bandwidth as a function of the parameter α;
- the use of coding to further mitigate reduced inter-signal distances;
- the possibility of higher frequency sinusoidal variation of the phase (e.g. 2 or 3 half cycles on the [0,*T*] interval instead of the single half cycle proposed here);
- using such a system for time of day broadcast messages, for users wishing to synchronize to the MSK time scale.

Finally we note that plots provided are for illustration/comparison purposes only, and do not represent official coverage diagrams for the DGPS system.

ABOUT THE AUTHORS

Richard J. Hartnett is a professor in electrical engineering at the U.S. Coast Guard Academy in New London, CT. He received his BSEE degree from the U.S. Coast Guard Academy, the MSEE degree from Purdue University, and his PhD in EE from the University of Rhode Island. His research interests include efficient digital filtering methods, improved receiver signal processing techniques for electronic navigation systems, and autonomous vehicle design.

Peter F. Swaszek is a professor in the Department of Electrical, Computer, and Biomedical Engineering at the University of Rhode Island. He received his PhD in electrical engineering from Princeton University. His research interests are in digital signal processing with a focus on digital communications and electronic navigation systems. He spent the 2007-08 academic year on sabbatical at the U.S. Coast Guard Academy working on a variety of RF navigation systems. Dr. Swaszek may be contacted at swaszek@ele.uri.edu.

Keith C. Gross (deceased Nov. 2010) was a professor and head of Electrical Engineering at the U.S. Coast Guard Academy in New London, CT. He received his BS degree and his MS in statistics and operations research from the U.S. Coast Guard Academy, and his MSEE and Ph.D. from Rensselaer Polytechnic Institute.

DISCLAIMER AND NOTE

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the Commandant, the U.S. Coast Guard, the Department of Homeland Security, or any agency of the U.S. Government.

[1] See for example, K. Maney, "Wireless text is logical basis for an emergency information system," http://www.usatoday.com/money/industries/technology/maney/2005-10-04-wireless-text_x.htm.

[2] P. Traynor, "Characterizing the limitations of third-party EAS over cellular text messaging services" (3G Americas Whitepaper, September, 2008).

[3] See also P. Traynor, W. Enck, P. McDaniel, and T. La Porta, "Exploiting open functionality in SMS-capable cellular networks," *Journal of Computer Security* 16 (2008): 713-742.

[4] R. Hartnett, K. Gross, M. McKaughan, P. Enge, P. Swaszek, G. Johnson, and A. Cleveland, "Novel signal designs for improved data capacity from DGPS radiobeacons," *Proc. Institute of Navigation National Technical Meeting*, San Diego, CA, January 26-28, 2004.

[5] P. Swaszek, R. Hartnett, P. Enge, G. Johnson, and K. Gross, "Performance of signal designs for improved data capacity from DGPS radiobeacons," *Proc. Institute of Navigation Annual Meeting*, Dayton, OH, June 6-9, 2004.

[6] G. Johnson, P. Swaszek, R. Hartnett, and P. Enge, "Transmitter effects and receiver prototyping for improved data capacity from DGPS radiobeacons," *Proc. Institute of Navigation GNSS 2004*, Long Beach, CA, September 21-24, 2004.

[7] R. Hartnett, P. Swaszek, and K. Gross, "Analysis of phase trellis overlay modulations for a DGPS secondary communications channel," *Proc. Institute of Navigation National Technical Meeting*, San Diego, CA, January 25-27, 2010.

[8] J. Anderson, T. Aulin, and C. Sundberg, *Digital Phase Modulation* (Plenum: New York, 1986), 147-180.

[9] R. Hartnett, et al., "Novel signal designs" (2004); Johnson, et al., "Transmitter effects and receiver prototyping" (2004); Swaszek, et al., "Performance of signal designs (2004)."

[10] R. Hartnett, P. Swaszek, and K. Gross, "Analysis of phase trellis overlay modulations for a DGPS secondary communications channel," *Proc. Institute of Navigation National Technical Meeting*, San Diego, CA, January 25-27, 2010.

[11] Ibid.

[12] Ibid.

[13] Ibid.

[14]*Broadcast Standard for the US Coast Guard DGPS Navigation Service*, COMDTINST M16577.1 (April 1993).